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HETEROGENEOUS WATER AND ENERGY END-USES AND IMPLICATIONS
FOR RESIDENTIAL WATER AND ENERGY CONSERVATION AND
MANAGEMENT

by

Adel “Mohammad Kheir” Abdallah

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

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UTAH STATE UNIVERSITY
Logan, Utah

2012

ABSTRACT

Heterogeneous Water and Energy End-Uses and Implications for Residential Water and
Energy Conservation and Management

by

Adel M. Abdallah, Master of Science

Utah State University, 2012

Major Professor: Dr. David E. Rosenberg
Department: Civil and Environmental Engineering

The thesis develops an integrated approach to model heterogeneous household water and energy end-uses and their linkages. The approach considers variations in behavioral and technological water-and-energy-use factors that affect indoor residential water- and energy-use in the U.S. Here, we use a recent, large, national, disaggregated household dataset of potable hot and cold water end-uses collected from eleven cities. We also use national energy data to estimate heterogeneous energy-uses for household water appliances including toilets, showers, faucets, clothes-washers, and dishwashers. First, probability distributions of water- and energy-use factors are identified, correlated, and compared among study sites. Then Monte Carlo simulations are used to calculate probability distributions for estimated households' water-and-energy-uses. Finally, linear regressions are used to find the relative effects of water and energy factors on household energy-use. Results show that water and energy distributions among households are heavily skewed, with the largest 14.6% of the users consuming 30.5% and 33.1% of water and energy, respectively. Water heater dispense temperature followed by faucet

flowrate have the highest relative effect on household energy-use and should be targeted to reduce household energy use. The approach improves prior homogenous and deterministic water-energy models and can help utilities select and size cost-effective collaborative water and energy conservation actions.

(53 pages)

PUBLIC ABSTRACT

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Indoor water-use consumes energy to heat hot water. Indoor water- and energy-use vary significantly among households due to variable household water-use behaviors and varying ages and efficiencies of water appliances. Also, the energy consumed to heat water varies among households and depends on water heater efficiency, heater thermostat setup, percentage of hot water in the final used water, and the cold water intake temperature. This research considers behavioral and technological variability in household water-and-energy-use to better understand water and energy linkages and help utilities target water and energy conservation actions to customer and appliances within their homes that the most affect water-and-energy-use.

We used a mathematical model to represent households' behavioral and technological variations to identify households' water and energy consumption and linkages. We used national detailed water consumption data for 400 single family households in 11 U.S. cities. Also we represented water heater types available in the U.S. and considered water heater intake cold water temperature across the U.S. We also

represented the water heater thermostat temperature through information form 343 plumbing/heating contractor firms throughout the U.S.

Research results show that the largest 14.6% of households use 30.5% and 33.1% of overall households' water and energy, respectively. We also found that water heater thermostat temperature and faucet flowrate are the most important factors that influence household energy-use. Turning down the water heater thermostat and adopting high-efficient faucets are the most effective actions to save household energy-use. The research findings can help water and energy utilities identify collaborative efforts to effectively save both water and energy.

DEDICATION

To my

Supportive father: Mohammad Kheir,

Companionate mother: Monira,

Lovely wife: Allia,

Buddy brothers: Khaled and Suliman,

Cute sisters: Samira, Sumayia, and Alaa, and

Fun extended family

This thesis is dedicated to all of them.

"قُلْ إِنَّ صَلَاتِي وَنُسُكِي وَمَحْيَايَ وَمَمَاتِي لِلَّهِ رَبِّ الْعَالَمِينَ"

“Say, Indeed, my prayer, my rites, my living and my dying are for Allah,
Lord of the worlds”

(Quran, Surat al-An'am: 162)

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Many thanks to my committee members for advising my research: Mac McKee, Laurie McNeill, and Gerald Sehlke. I am appreciative to Gerald for serving on my committee from the Idaho National Laboratory and for all his valuable feedback. Special thanks go to Dr. Laurie McNeill for supporting and encouraging me to pursue my master's degree at Utah State University.

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Adel “Mohammad Kheir” Abdallah

CONTENTS

| | Page |
|--|------|
| ABSTRACT..... | ii |
| PUBLIC ABSTRACT..... | iv |
| DEDICATION..... | vi |
| ACKNOWLEDGMENTS..... | vii |
| LIST OF TABLES..... | xi |
| LIST OF FIGURES..... | xii |
| CHAPTER | |
| 1. INTRODUCTION..... | 1 |
| 2. DISAGGREGATED NATIONAL WATER- AND ENERGY-USE DATASETS..... | 6 |
| 2.1 Water Data..... | 6 |
| 2.2 Energy Data..... | 9 |
| 3. STUDY METHODS..... | 10 |
| 3.1 Define and Extract Water-and-Energy-Use Factors..... | 10 |
| 3.2 Generate Probability Distributions of Water-and-Energy-Use Factors, Compare and Correlate Factors among Study Groups..... | 11 |
| 3.3 Develop Water-and-Energy-Use Model..... | 13 |
| 3.4 Identify Relative Effects of Water and Energy Factors in Household Energy-Use..... | 16 |
| 4. RESULTS AND DISCUSSION..... | 17 |
| 4.1 Heterogeneous Household Water-and-Energy-Use Factors..... | 17 |
| 4.2 Correlations among Water-Use Factors..... | 22 |
| 4.3 Monte Carlo Simulations of Heterogeneous Household Water-and- Energy-Uses..... | 24 |
| 4.4 Relative Effects of Water and Energy Factors in Household Energy-Use..... | 25 |

| | | |
|----|---|----|
| 5. | IMPLICATIONS FOR RESIDENTIAL WATER AND ENERGY CONSERVATION AND MANAGEMENT..... | 31 |
| 6. | CONCLUSIONS..... | 35 |
| | REFERENCES..... | 37 |
| | APPENDIX..... | 40 |

LIST OF TABLES

| Table | Page |
|---|------|
| 1 Sources and characteristics of disaggregated water end-use data..... | 8 |
| 2 Household groups used to compare and correlate the effects of water-use factors across cities and appliance performance levels | 8 |
| 3 Linear correlation results among water-use factors and appliances | 23 |
| 4 Characteristics of low, typical, and high water- and energy-users | 28 |
| 5 Appliances technical performance and frequency among low, typical, high water- and energy-users | 28 |
| A1 Current and historic water appliance technical performances..... | 41 |
| A2 Literature sources for water-energy parameters for major household appliances..... | 41 |

LIST OF FIGURES

| Figure | Page |
|--|------|
| 1 Schematic of a stochastic household water-and-energy-use model..... | 15 |
| 2 (A) Toilet use frequency is statistically similar across cities and time periods; (B) Toilet use frequency among Salt Lake City, UT households within the National group. Toilet flush volumes vary both within and across households..... | 18 |
| 3 (A) Toilet flush volume varies across study groups. (B) Toilet flush volumes vary within and across Slat Lake City, UT households. Most toilets in Salt Lake City households (within the National group) use more than the regulation standard of 1.6 gallon per flush (dashed green lines)..... | 21 |
| 4 Appliance hot water percentages show large variations among households and appliances | 22 |
| 5 Individual appliance water-and-energy-uses for 600 Monte Carlo simulations with average slope (linkage) listed in parenthesis in the legend. | 25 |
| 6 Heterogeneous household water- and energy-use for the five classes of users | 27 |
| 7 Relative effects of water and energy factors on household energy-use among low, typical, and high water- and energy-users. | 30 |

CHAPTER 1

INTRODUCTION

Historically, U.S. conservation efforts have largely been implemented separately across the water and energy domains (ACEEE and AWE 2011; Committee on Science and Technology 2009). There are, however, numerous benefits in coordinating water and energy conservation efforts and exploit water-energy linkages (ACEEE and AWE 2011; Committee on Science and Technology 2009). For example, conserving water can delay or downsize costly infrastructure upgrades (Vickers 2001), reduce the energy embedded to extract, treat, and distribute potable water plus collect and treat resulting wastewater, and the energy households expend indoors to heat water for sanitation. Energy expenditures in heating water comprise 17% of total household energy consumption excluding the energy embedded to deliver potable water to the household (Ryan et al. 2010). Understanding the linkages between water and energy is necessary for water and energy managers better plan and promote water and energy conservation actions.

Over the past two decades, U.S. federal agencies mandated several water and energy efficiency standards for household appliances. The first national energy efficiency standard took effect in 1990 and was updated in 2004 (Ryan et al. 2010). In 1992, the Energy Star Efficiency Program, a joint program of the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy (DOE), also helped improve water and energy technical performance efficiency in appliances like water heaters, clothes-washers and dishwashers (Energy Star 2012^a).

The Energy Policy Act of 1992 (EPAct), was the first water-use efficiency standard and mandated all toilets, showerheads, and faucets to operate below a maximum

volume or flowrate per use. Later, in 2006, EPA launched Water-Sense, a voluntary program to promote stricter water efficiency levels that reduced volume or flowrates by 20% from EPA standards (EPA-WaterSense 2010). As a result of these energy and water programs, major indoor appliance efficiencies have improved significantly over the past two decades. Yet, only recently have water and energy managers and researchers started recognizing the need to look at the synergistic effects of efficiency changes on water-and-energy-uses (ACEEE and AWE 2011; Committee on Science and Technology 2009).

Examples of synergistic energy-water models include the Watergy model (deMonsabert and Liner 1998), which estimates water and energy saved in a hypothetical federal facility through adopting higher efficient appliances (e.g., faucets and toilets). The model uses average behavioral (appliance use frequency) and technological values (appliance use flowrate or volume), and energy-use factors (water heater efficiency, intake and dispense temperatures) to estimate water and energy savings. Watergy also estimates expected payback periods of adopted high efficient appliances from saving water and energy.

The Alliance for Water Efficiency (AWE) model estimates water-use and water and energy savings for utilities that target conservation actions to sub-populations of their customer bases (AWE 2009). Conservation actions include for example high efficient toilets, faucets, and clothes-washers. The model uses average values for demographic, behavioral, and technological water-use factors. The model also uses average lump-sum energy parameters to estimate program-wide energy-use for each appliance per gallon of water-used (e.g., 0.14 and 0.11 KWh/gallon for respectively, clothes-washer and shower

end-uses). In this case, the energy parameters embed all energy factors like water heater efficiency, water heater intake and dispense temperatures, and the percent of hot water in the overall appliance water-use (hereafter, hot water percentage).

The DOE (2010) developed a water-energy-use model for U.S. households to estimate energy consumption in water heating. The model represents energy-use factors like water heater efficiencies (considering their models, market share, retirement age, growth rates, energy sources, etc.), water heater intake, and dispense temperatures. The DOE model estimates hot water-use through 14 proxy parameters, which include the number of residents in the household, the age of residents, and whether or not the household directly pays money for natural gas used to heat water. The model also estimates household energy-uses for different scenarios of households' adoption rates of higher efficient water heaters and their payback periods.

The above reviewed and other water and energy models use deterministic (average) approaches to estimate water demands by and savings from water conservation actions for major appliances in average or representative households for a homogenous populations (AWE 2009; Cheng 2002; deMonsabert and Liner 1998; Hopp and Darby 1980). Deterministic approaches assumed households behave similarly and have similar appliances and conditions and are necessitated by limited energy and water household data. In actuality, residential water and energy end-uses are heterogeneous and vary significantly among households with demographic (household-size), behavioral (use frequency or duration), technological (appliance use volume or flowrate, water heater intake and dispense temperatures, heater energy source, and heater efficiency), and geographic (climate, water availability) factors contributing to variations among users

(DOE 2010; Rosenberg 2007; Suero et al. 2012). When multiplied together to estimate water-and-energy-use, the uncertainties associated with these factors multiply rather than cancel. Thus, there is a strong need for more integrated, accurate, and heterogeneous approaches to estimate household water and energy linkages and identify targeted opportunities to coordinate water and energy conservation.

The availability of recent, large, disaggregated water and energy datasets now make heterogeneous analysis possible. These datasets include 1.4 million water-use events over 7,900 days by 400 single family households in 11 U.S. cities (DeOreo 2011; EPA 2005), water heater efficiencies for 709 water heaters models in the U.S., cold water heater temperatures for 74 cities across the U.S., and water heater dispense temperatures collected by 343 plumbing/heating firms throughout the U.S (DOE 2010).

In our research, we identify heterogenous water-and-energy-uses and linkages for five major indoor water end-uses (toilet, shower, faucets, clothes-washer, and dishwasher) and exploit the variations among users and linkages to recommend actions utilities can take to promote water and energy conservation. To do this, we first define appliance technical performance (flowrate or use volume per event), water-use behaviors (how many uses or use duration per household per day for each appliance), and demographics (number of residents, location) factors that affects water-use then extract distributions of facto values from the water-use database (DeOreo 2011; EPA 2005). We simultaneously pull distributions of water heater efficiency, intake, and dispense temperatures from the energy dataset (DOE 2010). Second, we generate probability distributions of water-and-energy-use factors, compare distributions of factors across eleven cities throughout the U.S., and identify correlations among them. Third, we used

Monte Carlo simulations to propagate the effects of heterogeneous and correlated water-energy-use factors and forecast resulting household water-and-energy-uses. Finally, we use linear regressions to find the relative effects of water and energy factors on household energy-use. This approach helps systematically identify water and energy relationships among heterogeneous residential water-users and characteristics of users that use high water and energy. This method helps utilities in targeting users of high consumption and recommending collaborative water and energy conservation campaigns.

Chapter 2 describes the nationwide disaggregated water- and energy-use datasets we draw on. Chapters 3 and 4 present the study methods and our results. Chapter 5 discusses the implications of our results and presents our recommendations for coordinated water and energy management and conservation. Chapter 6 provides our conclusion.

CHAPTER 2

DISAGGREGATED NATIONAL WATER-AND-ENERGY-USE DATASETS

2.1 Water Data

Our study uses a 250 mega-byte disaggregated water end-use dataset collected by Aquacraft, Inc. and funded by the EPA which monitored 393 single-family households across 11 U.S. cities between 2000 and 2011 as part of the Retrofit and New Single Family Homes studies (DeOreo 2011; EPA 2005) (Table 1). We also use related energy-use factors from a U.S. Department of Energy published dataset on water heater efficiencies for 709 water heaters models in the U.S., cold water heater temperatures for 74 cities across the U.S., and water heater dispense temperatures data collected by from 343 plumbing/heating firms throughout the U.S (DOE 2010).

In the Retrofit study, Aquacraft logged and disaggregated end-use data from 88 households in Seattle, WA, Oakland, CA, and Tampa, FL for two weeks before and four weeks after each household was retrofitted with high efficient appliances (toilet, shower, faucet, and clothes-washer). They quantified average water savings gained by retrofitting low-efficient appliances with high-efficient appliances that comply with EPA standards. Additionally, Aquacraft installed meters in 20 households in Seattle and Oakland to measure hot water end-uses and estimate hot water percentages. In the New Single Family Homes study (DeOreo 2011), Aquacraft logged and disaggregated baseline end-use data over two weeks from 305 new homes built after January 2001 in nine cities across the U.S. (Salt Lake City, UT; Aurora and Denver, CO; Eugene, OR; Las Vegas, NV; Phoenix, AZ; Roseville, CA; and Palatka and Tampa, FL). Aquacraft also measured baseline water-use for 25 new, Water-Sense high-efficiency homes (HEH) built after

2007 (DeOreo 2011). Table A1 in the Appendix show how these EPAAct and HEH appliance performances compare to appliance water efficiency improvements over the last five decades.

In collecting the national water-use dataset, Aquacraft coordinated with water utilities to select representative single-family houses in terms of total annual water-use for each utility service area. Selected households were contacted through mail to ask for cooperation. Then water end-use data for participating households were recorded using a magnetic sensor that records water flows through the household water meter at ten second intervals. Trace Wizard[®] software was used to disaggregate the volume and duration of each water-use event from toilets, showers, clothes washers, dishwashers, baths, faucets, irrigation, leaks, etc. (Mayer et al. 1999). Demographic and detailed household characteristics data were also collected through households survey (DeOreo 2011).

Disaggregated data were stored in an Access database. Each household was given a unique identity number including monitored water-use events for each appliance (i.e., volume, flowrate, duration). The Flow Trace analysis differentiated individual dishwater and laundry machine cycles, but in this study, we lumped these cycles into a single use event for the appliance. Also, the Flow Trace analysis method disaggregated water-uses to major appliances (e.g., toilets and faucets) but did not separate individual appliances (e.g., bathroom faucet #1, or kitchen faucet #2). Pressure-based sensors can monitor water-use from multiple appliances of the same type in a house but are not yet market ready (Larson et al. 2012).

To help compare and correlate the effects of water-use factors across the studies, cities and appliance efficiency levels, we created four household-data groups: (i) National, (ii) Pre-Retrofit, (iii) Post-Retrofit, and (iv) High Efficient Homes (HEH) (Table 2). These groups allow us to compare technological and behavioral water-use factor for houses built pre-EPAAct, houses with EPAAct standard efficient appliances, and high efficient homes. We used data from the National group of nine cities to model heterogeneous water-and-energy-uses, identify water-energy linkages, and discuss implications for water and energy conservation and management.

Table 1: Sources and characteristics of disaggregated water end-use data (DeOreo 2011; EPA 2005)

| Dataset | Number of Cities | Data collection period | Number of houses | monitoring days | cumulative water-use events |
|-------------------------|-------------------------|-------------------------------|-------------------------|------------------------|------------------------------------|
| New Single Family Homes | 9 | 2005-09 | 305 | 3,885 | 648,719 |
| Retrofit | 3 | 2000-03 | 88 | 4,036 | 753,076 |

Table 2: Household groups used to compare and correlate the effects of water-use factors across cities and appliance performance levels (DeOreo 2011; EPA 2005)

| Group | Year houses built | Efficiency standard | Sample size (# of households) |
|----------------------|--------------------------|----------------------------|--------------------------------------|
| National | After 2001 | EPAAct 1992 | 280 |
| Pre-Retrofit | Before 1992 | None | 88 |
| Post-Retrofit | Before 1992 | EPAAct 1992 | 88 |
| High Efficient Homes | After 2007 | Water-Sense | 25 |

2.2 Energy Data

The energy-use dataset comprises water heater efficiencies, water heater intake temperatures, and heaters dispense temperatures for the U.S households (DOE 2010). DOE collected and analyzed historical, current, and projected water heaters shipments in the U.S. market from water heaters issued by manufactures and listed in their corporate disclosure reports. The study observed and analyzed 709 water heater models; they reported the market share (%) in 2010 for major energy sources of water heaters: gas-fired (41.8%), tank-less gas-fired (11.6%), electricity-fired (46.3%), and oil-fired (0.3%). DOE further disaggregated each water heater type by seven to nine levels of insulation and heating technology. The storage volume and market share for each water heater model, as well as average annual temperature of water supplied to customers in 74 cities across the U.S., were also reported. The reported water heater dispenses temperatures were based on 343 plumbing/heating contractor firms throughout the U.S. The DOE study also found that 60% of households set their water heater dispense temperature at 120 °F, while the remainder vary between 120 to 140 °F (DOE 2010).

In addition to hot water dispensed from the water heater, dishwashers also consume energy to run internal pumps, control solenoids, dryers, and power the booster heater. The energy consumed by the first three operations is typically 0.49 KWh/load and similar among different dishwasher models and sizes, while the energy consumed to boost the dishwasher water temperature up to 140 °F is a linear function of the dishwasher technical performance (volume) (Hoak et al. 2008). The next section describes how we used these water and energy datasets to model and forecast heterogeneous water and energy end-uses and identify water-energy linkages.

CHAPTER 3

STUDY METHODS

To forecast heterogeneous water and energy end-uses and identify water-energy linkages, we first extracted and defined distributions of values for behavioral, technological and demographical water- and energy-use factors from the datasets. Second, we generated probability distributions of water-and-energy-use factors, compared distributions of factors among study groups, and identified correlations among them. Third, we developed household water-and-energy-use models using Monte Carlo simulations. Lastly, we identified the relative effects of water and energy factors in modeled household energy-use. We further describe each step as follows.

3.1 Define and Extract Water-and Energy-Use Factors

First, we screened the water end-use data for inconsistencies in format and excluded houses with no household-size reported. To simplify the comparisons and analysis, we pooled the Post-Retrofit collection periods (2 weeks and 6 months of retrofits) for each household. We only estimated technological factors for the HEH group since the household-size was not reported.

We defined water-use demographic, technological, and behavioral factors for each household as the; (i) household-size (number of occupants), (ii) appliance or fixture performance [gallons per minute] or toilets, clothes-washers, or dishwashers water-use volume [gallon per flush or per load], and (iii) frequency of duration of water-use events per day or week [toilet flushes per household per day, clothes-washer loads per household per week, minutes of shower or faucet use per household per day]. We extracted water-

use factors using the Structured Query Language in Microsoft Access. We used the daily frequency for toilet, shower, and faucet appliances since they are generally used daily in every household. However, we used weekly use frequency for dishwasher and clothes-washer appliances since they are used less frequently.

Having the water-use factors defined, we extracted distributions of factor values using the Structured Query Language in Microsoft Access. To find an individual household water-use behavioral value, we summed the number of water-use events or use-minutes for each day, and then we found the household's average behavioral value over the monitoring period days. To find a technological water-use value for a household, we found an average volume or flowrate as a household value over the monitoring period events. Here, our focus is on daily household behavioral water-use values and variations among households which differ from aggregate values for populations of households as used previously in (DeOreo 2011; Mayer et al. 1999). We repeated the extraction process for each household group (National, Pre-Retrofit, Post-Retrofit, HEH).

We calculated hot water percentages for shower, faucet, clothes-washer, and dishwasher water-uses in an individual household by first summing then dividing the household's hot water volume by the total water volume used over the monitoring period. We used an overall hot water percentage instead of an average daily percentage because the data showed some asynchronization and random time shifts between the bulk and hot water meters (DeOreo and Mayer, personal communication, 2011). We censored three household hot water percentages above 100% that we attribute to measurement error (103% for faucet use in one household; 114% and 124% for dishwasher uses in two households).

3.2 Generate Probability Distributions of Water-and Energy-Use Factors, Compare and Correlate Factors among Study Groups

After extracting the end-use data, we used Matlab to produce empirical probability distributions that show variations of behavioral and technological factors among households for each appliance. For the energy factors, we generated the probability distribution of water heater efficiency considering all reported water heater models and their market share among households. We used the maximum entropy principle to generate a uniform probability distribution for heater dispense temperature for the 40% of households who set their heater dispense temperature between the known bounds 120 °F and 140 °F (Tribus 1969).

We used non-parametric statistical tests to compare distributions among groups since the non-parametric test makes no assumption about the distribution of the data. Here, we assume households are independent from each other. We used the Kolmogorov-Smirnov (K-S) test to statistically test the null hypothesis that the cumulative distributions of water-use factors derived from two sample groups are similar (Massey 1951). The K-S test statistic (D) represents the maximum absolute difference between the two cumulative distribution curves. We rejected the null hypothesis of similarity when D was larger than a criteria statistic at the specified confidence interval. We used the non-parametric Kruskal-Wallis (K-W) test to compare factors in multiple household groups (Kruskal and Wallis 1952). K-W is as a nonparametric version of the classic one-way ANOVA and an extension of the Wilcoxon rank sum test to more than two groups. When the K-W test indicates that at least one compared factor is different among the others, we

used Tukey's Honestly Significant Difference test to find statistically different and similar factors among groups at the specified confidence level.

Finally, we used a non-parametric Spearman's rank linear correlation technique between demographical, behavioral, and technological water-use factors to test statistical correlation or dependence among factors. The test examines the null hypothesis of no correlation against the alternative that there is a correlation at the 95% confidence level. As shown in section 4.2, we found that demographic and behavioral factors are correlated. To consider this correlation in the water- and energy-use model, we generated separate distributions of water-use frequencies for each household-size (one to nine capita: here the household-size took integer values). This approach was also used for separating faucet and dishwasher uses for households that had a dishwasher (81% of the National group).

3.3 Develop Water- and Energy-Use Model

We used Monte Carlo simulations (Law and Kelton 1991) to correlate and propagate the uncertainties of stochastic (the ranges and likelihoods or probabilities of values that each factor can take) water-and energy-use factors identified from the empirical water and energy data sets, find the composite probability distributions of water-and-energy-uses, and their interdependencies.

Each Monte Carlo sample represents an independent household with its corresponding and correlated demographical (household-size), behavioral (e.g., flush per household per day), and technological (e.g., gallon per flush) attributes sampled from the underlying empirical probability distributions for the water and energy factors identified in section 3.2. We used the inverse transform sampling method (Steyvers 2011) to

generate random values from identified probability distributions. Monte Carlo sampling allows us to embed correlations among stochastic water and energy factors identified in step 3.2 that were not considered in the original, separate, empirical water and energy data sets.

Figure 1 shows the stochastic-water-and-energy-use model estimates water-and-energy-use as follows: (i) sample household-size and sample presence/absence of a dishwasher, (ii) sample values for appliance technological factors, (iii) sample from appliance water-use frequency distributions that correlate to the sampled household-size, (iv) multiply the sampled values in step two by the sampled value in step three to find household water-use for each appliance. Then, (v) sample water heater intake temperature, dispense temperature, heater efficiency, and hot water percentage, and (vi), use the sampled values for the energy parameters, estimated water-use, and the first law of thermodynamics to estimate household energy-use. We repeated these steps for each water-use appliance in each of 48,000 Monte Carlo simulated households.

Energy-use estimates multiply the estimated water-volume (e.g., shower water-use) by the temperature difference between the sampled potable cold intake and hot water dispense temperatures, sampled hot water percentage and the specific heat (Sh) of water ($Sh=0.00244 \text{ KWh/gal } ^\circ\text{F}$), then divide by sampled water heater efficiency. This method estimates energy-use at the heater dispense point and embeds energy lost in household pipes along the way to the point of source of water-use, and contrasts with estimation at the point of water-use as in (Weihl and Kempton (1985) (see Table A2 in the Appendix). For dishwasher energy consumption, we also add the energy consumed to run internal pumps, control solenoids, dry, and drive an internal booster heater (Hoak et al. 2008).

Finally, we calculated the composite distribution of household water-and-energy-uses by summing the water-and-energy-uses of appliances for each Monte Carlo household sample. Then we used the K-S test to verify model results against observed household toilet, shower, faucet, dishwasher, and clothes-washer, and overall water-use in the Aquacraft end-use data. Verification insured we identified the appropriate water-use factors and correctly implemented Monte Carlo sampling and modeling. We could only verify water-use estimates since we have no energy-use data.

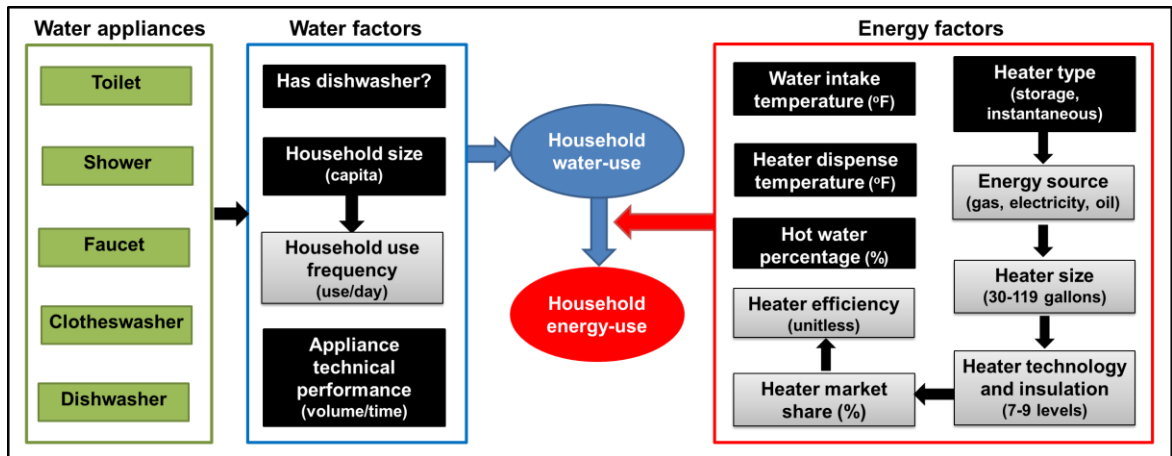


Figure 1: Schematic of a stochastic household water-and-energy-use model. Black boxes represent independent factors, grey boxes represent dependent factors, and arrows show dependencies

3.4 Identify Relative Effects of Water and Energy Factors in Household Energy-Use

We used multiple linear regressions to explain estimated household energy-use (dependent variable) in terms of explanatory variables like technological and demographic water and energy factors and find the relative effects of factors on household energy-use. We report the coefficient of determination, R^2 value, which represents the proportion of the total variability in the dependent variable that is explained by the regression equation. We also report the elasticity of water and energy factors on household energy-use to describe the relative effects of factors and facilitate comparison among them. The elasticity represents the percentage change in household energy-use for 1% change in a water or energy factor. The elasticity values allow us to identify the most effective water and energy conservation actions to target in order to reduce a household's energy-use.

CHAPTER 4

RESULTS AND DISCUSSION

The section presents results that describe the distributions of identified, correlated, and compared water-use factor values. It presents also water and energy Monte-Carlo simulations results and the relative effects of water and energy factors on household energy-use.

4.1 Heterogeneous Household Water- and Energy-Use Factors

Demographic

The K-S statistical test results show that the distributions of household-size among the Retrofit Project and the National groups are statistically similar at the 95% confidence level with averages near the U.S. average household-size of 2.6 people (U.S. Census Bureau 2010). Results also show that household-sizes of households that do and do not have dishwashers are statistically similar.

Behavioral factors

The W-S non-parametric-ANOVA test results suggest that household water-use behaviors are statistically similar across the National, Pre-Retrofit and Post-Retrofit groups and study sites for each appliance (P values= 0.426, 0.117, 0.322, 0.104, and 0.831, respectively, for toilet, shower, faucet, clothes-washer, and dishwasher). More importantly, water-use behaviors did not change after retrofitting appliances, which suggest that higher efficient appliances have no effect on appliance-use frequency (Figure 2-A). Although aggregate water-use behaviors are similar across cities, behaviors do vary both across households and within households from day to day (Figure 2-B). For

example, household #14 flushed the toilet more frequently with high daily variability while household #15 flushed the toilet less frequently with consistent flushing frequency from day to day. Toilet-use frequency variations within households show the dynamics of household water-use behavior while variations across households show the behavioral differences among households. We used appliance-use frequency variations across households to model water-and-energy-uses for the households' population.

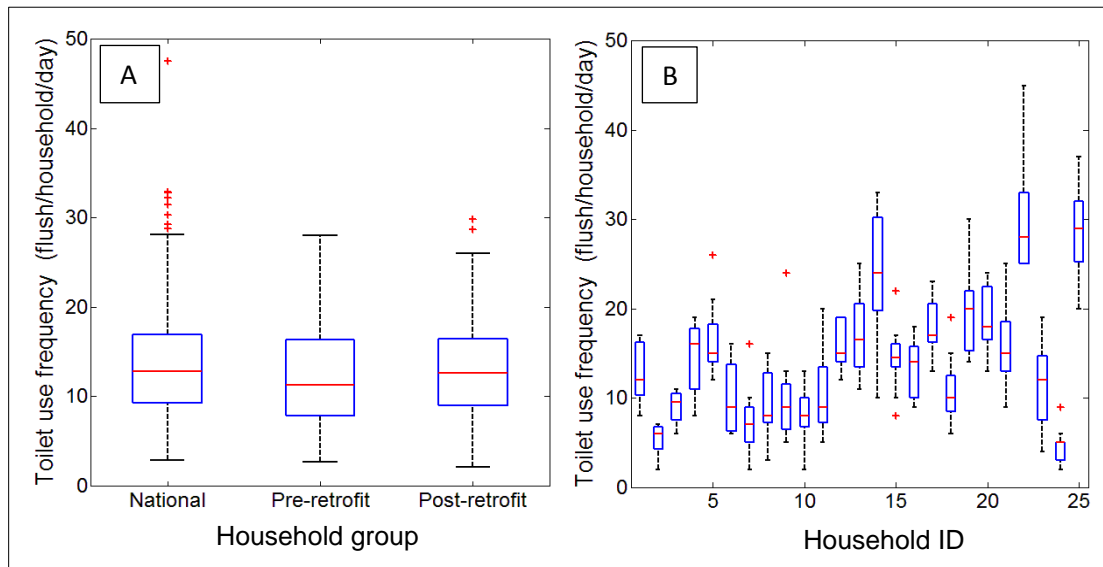


Figure 2: (A) Toilet use frequency is statistically similar across study groups; (B) Toilet use frequency among Salt Lake City, UT (households within the National group) varies both within and across households.

Technological factors

As expected, the K-S test results suggest appliance technical performance varies significantly across National, Pre-Retrofit, Post-Retrofit, and HEH groups for all appliances (toilet, shower, faucet, clothes-washer, and dishwasher). The Pre-Retrofit group has the lowest appliance efficiency and the HEH group has the highest efficiency. These differences suggest household with low-efficiency appliances can conserve water if they upgrade to more efficient ones. Interestingly, toilet flush-volumes are statistically similar for Post-Retrofit (EPA standards) and HEH groups and suggest HEH toilets are not achieving the 20% reduction in water-use intended by the Water-Sense standards.

To further explain variation in appliance technical performance, we discuss toilet flush volume among the groups in more detail (Figure 3). Most toilets in the National group flush above the regulation standard of 1.6 gallons per flush (1 gallon = 3.81 liter) and suggest there is a need for toilet compliance measures. The Post-Retrofit group shows less flush volume variation and complies with the regulation standard. The HEH group toilets comply with the standards but they flush over the 1.28 gallon per flush standard as specified by Water-Sense. Toilet efficiency of the National and the Post-Retrofit groups is expected to comply with the efficiency standard by the EPA. However, water-use in the National household group was monitored after an average of 5.2 years (assuming appliance age is similar to house age for houses built after 2001), whereas water-use in Post-Retrofit household group was monitored within six months after being retrofitted. Toilet performance results suggest that appliance performance decays with time, toilets were not installed properly, or appliances malfunctioned. It is important to note that in this disaggregated end-use data, toilets leaks are separated from the toilet flush events (Mayer et al. 1999).

In addition to variation among study groups, appliance performance also varies both across and within households (Figure 3-B). This variation parallels heterogeneous results seen in Figure 2 for behaviors and appliance uses. Appliance performance variations within household show the range of values that a particular appliance performs within the household while variations across households show different levels of efficiency standards among households. Here, we used appliance performance variations across households to model water-and-energy-uses for the households' population.

Clothes-washer and dishwasher performances are different among all groups and retrofitting with more efficient appliances can yield important water savings (though, dishwasher performance in the Pre- and Post-Retrofit groups are similar because dishwashers were not retrofitted). Shower flowrates in the HEH are lower than the Post-Retrofit, National, and Pre-Retrofit groups. Also, faucet flowrates in the Post-Retrofit group are lower than the HEH and National, and Pre-Retrofit groups. Both faucets and showers in the National groups can save water by retrofitting their faucets to Water-Sense faucets and showers. However, showers and faucets will save water less than toilets and clothes-washers since these earlier appliances perform close to Water-Sense efficiency standards than the later appliances.

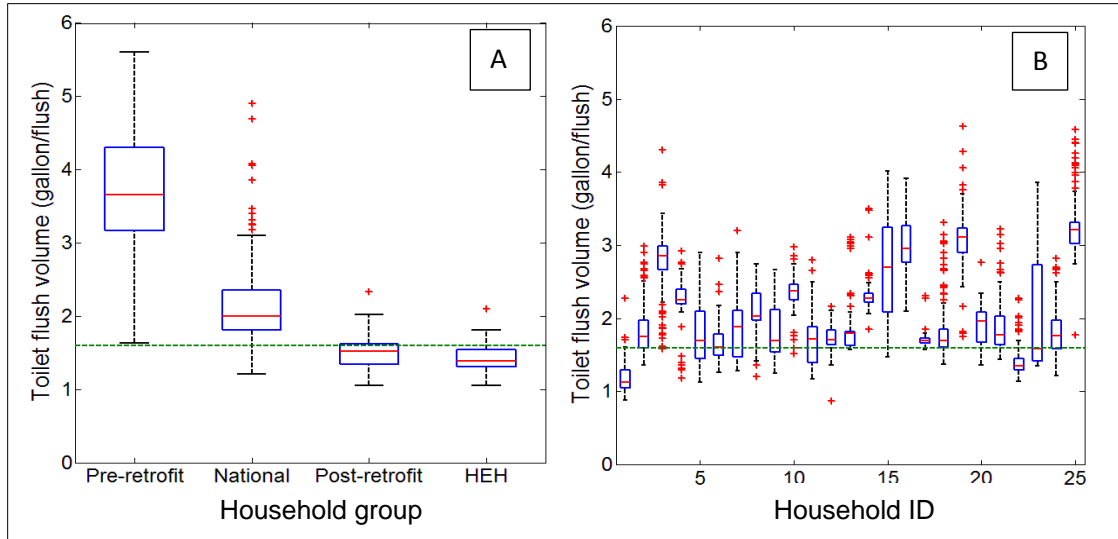


Figure 3: (A) Toilet flush volume varies across study groups. (B) Toilet flush volumes vary within and across Salt Lake City, UT households (1 gallon = 3.81 liter). Most toilets in Salt Lake City households (within the National group) use more than the regulation standard of 1.6 gallon per flush (dashed green lines)

Hot water percentages in appliance water-use

Hot water percentages varied significantly among households and appliances, with clothes-washers having the lowest and dishwashers the highest fraction of hot water in the end-use (Figure 4). K-S test results show that showers and faucets have statistically similar hot water percentages ($D = 0.28$; $P = 0.39$ at 95% confidence level). Large error bars on the box-and-whisker plot indicate large variations in hot water percentages among households and suggest the hot water percentage will significantly affect estimated energy-use and savings. In the Retrofit groups, K-W tests results show the hot water percentage is similar for Pre- and Post-Retrofits for all appliances ($P = 0.22, 0.78, 0.06$, and 0.34 for, respectively, showers, faucets, clothes-washers, and dishwashers).

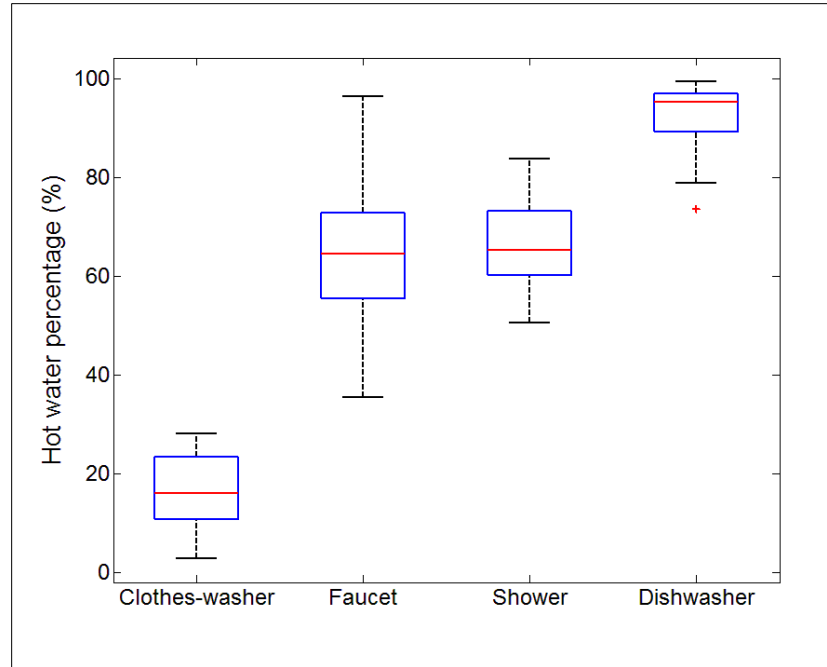


Figure 4: Appliance hot water percentages show large variations among households and appliances

4.2 Correlations among Water-Use Factors

Linear correlation between household-size against water-use behaviors, technological factors, and other factors for each study group show that household-size influences water-use behavior significantly for all appliances except the dishwasher in the Retrofit group (Table 3). Results also show that household-size has the largest influence on faucet use duration, followed by the shower use duration, toilet flushing, clothes-washer, and dishwasher use-frequency. Household-size has less influence on clothes-washer- and dishwasher use-frequency. In contrast there is no significant statistical correlation between household-size and appliance technical performance, or between water appliance technical performance and use frequency. House age also has no statistical correlation with appliance technical performance which suggests either; (i)

flowrates, flush, or load volume do not change with time, or (ii) households install more efficient appliances over time.

Results also show that appliance hot water percentages are independent from one-another and from appliance technical performance. For example, households that use a high percentage of hot water in shower could use a low or high percentage of hot water in clothes-washer. For each study group, we also conducted cross correlation analysis for technical performance factors among appliances. Correlation results show that appliance technical performance is independent from the performance of other appliances at the 99% confidence level. For example, shower and faucet flowrates in a particular household are independent of one-another. However, behavioral factors (use frequency) are correlated (e.g., higher shower use frequency implies higher toilet-use frequency, etc.). We used these correlation results to stochastically model water-and-energy-uses and Monte Carlo simulations to simulate linkages among factors.

Table 3: Linear correlation results among water-use factors and appliances

| Linear correlation between? | | Toilet | Shower | Faucet | Clothes-washer | Dishwasher |
|-----------------------------|-------------------------|--|-----------------|-----------------|-----------------|------------------|
| | | Correlation statistically significance at 95 % confidence level? | | | | |
| Household-size | Appliance Use frequency | YES | YES | YES | YES | YES ^a |
| Appliance performance | Appliance use frequency | NO ^b | NO ^c | NO ^b | NO ^b | NO |
| Appliance performance | Household-size | NO | NO | NO ^d | NO | NO ^b |
| House age* | Appliance performance | NO ^e | NO | NO | NO | NO |
| Hot water % | Appliance performance | NO | NO | NO | NO | NO ^f |

^a In the Post-Retrofit group, correlation is not significant

^b In Post-Retrofit group, correlation is not significant at the 99 % confidence level.

^{c, d} In the National group, correlation is significant but slope of regression is very small =-0.0091 and -0.0271 respectively

^e In the National group, correlation is no significant at 99% confidence level

^f In Post-Retrofit (second monitoring period), correlation is not significant at 99% confidence level

* House age ranges from 2-8 years for National group and 6-114 years for Retrofit group.

4.3 Monte Carlo Simulations of Heterogeneous Household Water-and-Energy-Uses

We used Monte Carlo simulations for 48,000 households to propagate the correlated and independent uncertainties in water and energy factors to estimate heterogeneous household water-and-energy-uses and linkages. Results show large variations in energy- and water-uses, among both households and appliances (Figure 5).

Clothes-washers and toilets have, respectively, the highest and the lowest energy-water linkage (KWh of energy per gallon of water-use). We also evaluated slopes of linear regression lines fit between the appliance data points. Toilets have a slope of zero and no linkage because they use only cold water and require no household energy expenditure. The water-energy slopes help identify effective water conservation action that save more energy per water saved (Figure 5). Altogether, the overall indoor household energy-water linkage is 0.086 KWh/gallon. This overall indoor household water-energy linkage shows the direct energy needed to heat indoor water per gallon of water-used and can be compared against the embedded energy to deliver potable water to the household and to treat the resulting wastewater.

The K-S results show that modeled and observed distributions of water-uses among National households (both for individual appliances and overall household water-use) are statistically similar ($D=0.08$, $P=0.05$ at 99% confidence level for the overall household water-use). This result suggests that no errors were made in identifying water-use factors and the Monte Carlo simulation model correctly represents water appliances and household water-use.

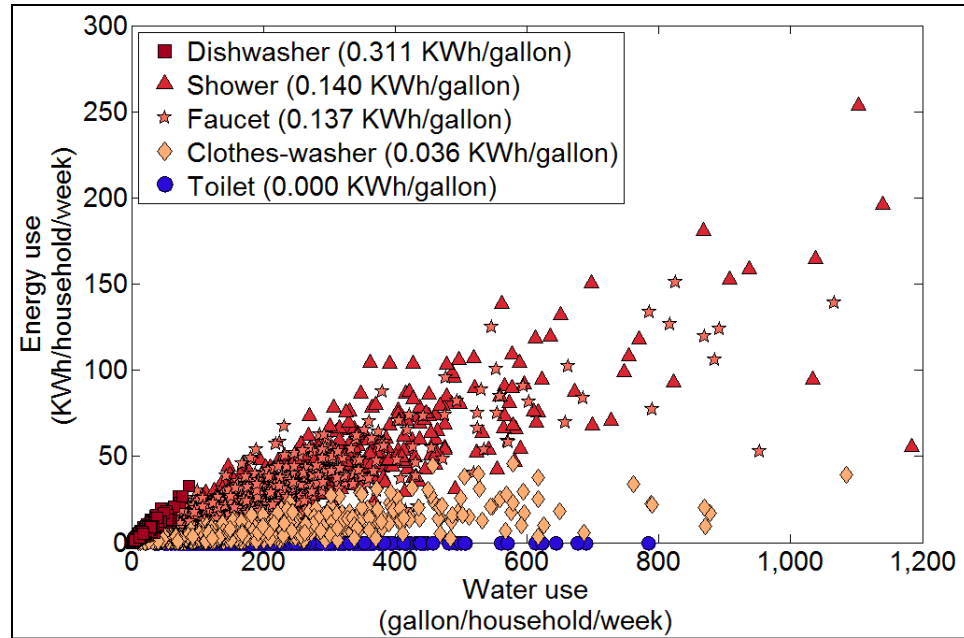


Figure 5: Individual appliance water-and-energy-uses for 600 Monte Carlo simulations with average slope (linkage) listed in parenthesis in the legend.

4.4 Relative Effects of Water and Energy Factors in Household Energy-Use

To better understand the factors influencing the heterogeneity in household water-and-energy-uses, we aggregated appliance water-and-energy-uses by household and divided the population of the simulated household into five major classes (Figure 6). Households in the low uses class showed water-and-energy-uses below the 20th percentiles of 455 gallon/week and 36 KWh/week for the overall simulated population. Households in the high class use water and energy above the 80th percentiles of 1,203 gallon/week and 105 KWh/week. Typical households use water and energy between the 20th and 80th percentiles. A fourth class shows low energy and typical or high water-uses while a fifth class the converse. The high water-and energy-use class comprises 14.6% of households but uses 30.5% of the overall water and 33.1% of the overall energy-used by households in the sample. Thus, the distributions of household water and energy

distributions are heavily skewed and suggest that a small number of households use large quantities of water and energy.

For each household water- and energy-use class, we calculated summary statistics for water-and-energy-uses and selected factors (Table 4 & Table 5). Statistical comparisons for water and energy factors among the high, typical, and low use classes show that standard deviations of water-and-energy-uses and factors for households in the high-use category are much larger than corresponding values in the low- or typical-use classes. In other words, low-use households are largely similar to each other while high-use households vary significantly. In general, high water-and-energy-users have larger households, lower heater efficiency, lower intake temperature, higher water heater dispense temperature, use appliances two to three times more frequently than low users, and have less efficient appliances. The K-S comparison results show that dishwasher presence/absence in the house does not seem to influence the user class (Table 4).

The class of low-energy, high-water users comprise a much smaller percentage of the household sample and are generally similar to typical users except they have less efficient water appliances, use appliances more frequently, have more efficient heaters, lower dispense temperatures, and they have higher intake temperatures (results not shown). Likewise, high-energy and low-water users are generally similar to typical users except they have more efficient water appliances, use appliances less frequently, have low efficient heaters, higher dispense temperatures, and they have low intake temperatures (results not shown). In short, households with high efficient water appliances might have low efficient water heaters and high dispense temperatures or vice versa.

To find the relative effects of water and energy factors on household energy-use, we used multiple linear regressions for the low, typical, and high user classes to relate modeled household energy-use (dependent variable) to several explanatory water and energy variables. We ran separate regressions for the low, typical, and high user classes and found that the independent factors account for a large portion of the variation in energy-use (Figure 7). We report regression coefficients as elasticity values (percent change in energy-use associated with 1% change in the water or energy factor) to normalize across factors and use classes. To obtain an elasticity value, we multiply the regression coefficient for a factor (e.g., shower technical performance) by the factor's average value within the user class then divide by the average energy-use within the user class.

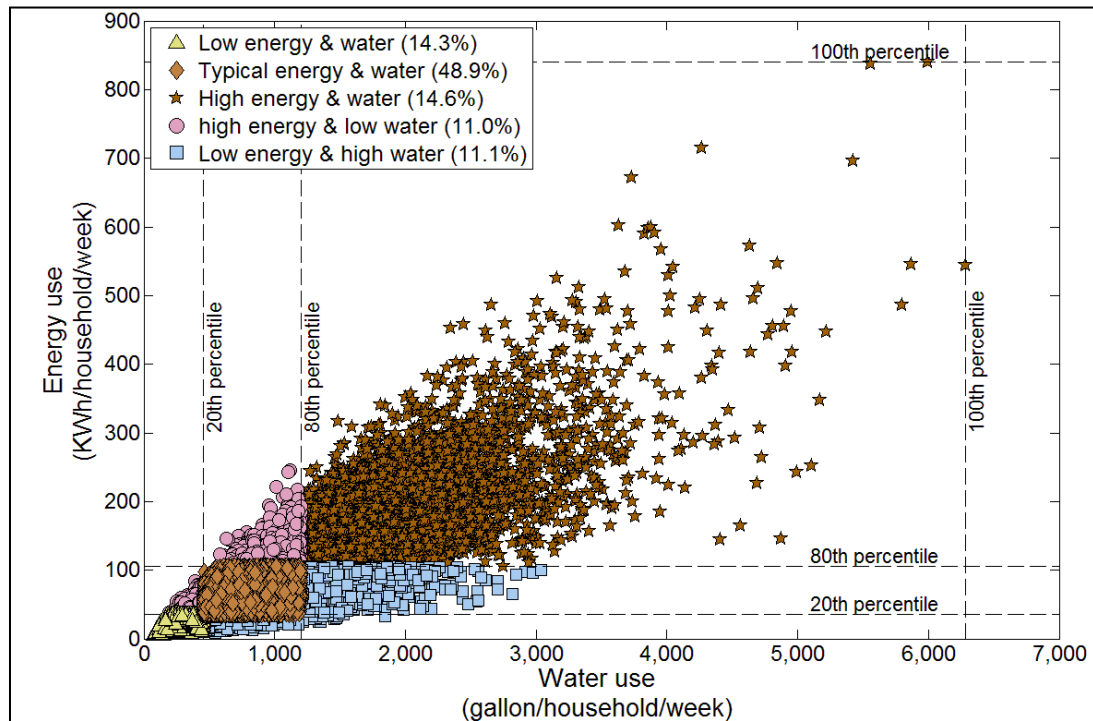


Figure 6: Heterogeneous household water-and-energy-use for the five classes of users

Table 4: Characteristics of low, typical, and high water- and energy-users

| Characteristic | Unit | Low users | Typical users | High users |
|---------------------------|-----------------------|------------------------|---------------|------------------------|
| Water-use | gallon/household/week | 316.7±81.0 | 761.4±191.4 | 1821.0±565.2 |
| Energy-use | KWh/household/week | 24.5±6.7 | 64.0±17.8 | 170.9±64.6 |
| Household-size | capita | 2.0±0.9 | 2.5±1.2 | 3.7±1.5 |
| Heater efficiency | unitless | 0.85±0.26 | 0.78±0.18 | 0.74±0.17 |
| Intake temperature | °F | 60.3±9.3 | 58.6±9.1 | 57.1±8.8 |
| Dispense temperature | °F | 123.5±5.7 | 124.0±6.1 | 124.8±6.5 |
| Dishwasher presence ratio | % | 0.79±0.41 ^a | 0.81±0.39 | 0.77±0.42 ^a |

^a statistically similar at 95% confidence level

Table 5: Appliances technical performance and use frequency among low, typical, high water- and energy-users

| Class | Variable | Toilet | Shower | Faucet | Clothes-washer | Dishwasher |
|----------------|--------------------------|------------|-------------|-------------|---------------------------|---------------------------|
| Low | Performance ^a | 1.8±0.3 | 1.6±0.3 | 0.8±0.11 | 23.1±8.9 | 3.8±2.2 |
| | Frequency ^b | 52.4±17.9 | 59.7±22.6 | 90.6±46.8 | 2.5±1.3 | 1.8±1.5 |
| | Hot water % | 0.0 | 0.659±0.097 | 0.636±0.135 | 0.167 ^c ±0.072 | 0.917 ^d ±0.074 |
| Typical | Performance | 2.1±0.4 | 2.0±0.39 | 1.0±0.2 | 33.3±10.6 | 5.0±2.7 |
| | Frequency | 91.3±27.3 | 119.1±46.7 | 172.5±79.8 | 5.6±2.5 | 2.2±1.9 |
| | Hot water % | 0.0 | 0.669±0.098 | 0.644±0.135 | 0.169±0.072 | 0.918±0.074 |
| High | Performance | 2.2±0.7 | 2.5±0.8 | 1.4±0.5 | 43.9±11.2 | 6.2±3.9 |
| | Frequency | 108.9±49.4 | 148.6±89.9 | 186.0±174.8 | 7.3±4.2 | 2.6±2.6 |
| | Hot water % | 0.0 | 0.676±0.099 | 0.654±0.136 | 0.172±0.072 | 0.920 ^d ±0.073 |

^a gallon/flush for toilet, gallon/minute for shower and faucet, and gallon/load for clothes-washer and dishwasher

^b flush/household/week for toilet, minute/household/week for shower and faucet, and load/household/week for clothes-washer and dishwasher

^{c,d} statistically similar at 95% confidence level

As shown in Figure 7, water heater dispense temperature has the largest relative influence on household energy-use followed by the faucet flowrate, intake temperature, and heater efficiency. Other factors like the clothes-washer technical performance and shower hot water percentage have much smaller relative effects. For example, decreasing the water heater dispense temperature by 10% (12 degree °F) for typical user class would decrease the household's energy-use by 13% whereas increasing water heater efficiency by 10% for a household in the high user class would reduce household energy-use by 7%.

This result suggests managers should ask people to turn down their water heater to 120 °F to save energy more than any other action.

Generally, elasticity values are similar across the three user classes except for the elasticity values associated with the faucet and shower flowrates. Faucet and shower elasticity values are much higher in the low user class because faucet and showers comprise larger portions of total household water- and-energy-use compared to other the typical or high user classes. Keep in mind that although many elasticity values are similar across the classes, the overall energy saved can differ among classes because the classes have different energy-uses. For example, decreasing the dispense temperature of the water heater by 10% would decrease household energy-use by 12%, 13%, and 15% or 2.9, 8.3, and 25.6 KWh/household/week for low, typical, and high users, respectively. Also, faucet flowrates have higher elasticity values of 1.4%, 0.8%, and 0.7% compared to heater efficiency elasticity values of 0.5%, 0.6%, and 0.7% for low, typical, and high users, respectively. Thus, retrofitting existing faucets with 10% more efficient flowrate faucets can save more energy than retrofitting water heaters with a 10% efficiency improvement. These results suggest water and energy utilities can beneficially collaborate to fund faucet retrofit programs and save both water and energy.

Separate regressions of estimated water-and-energy-uses against the presence of a dishwasher, faucet flowrate, and other explanatory variables yield negative elasticity values for dishwasher variable and suggest that installing a dishwasher will save both water and energy. These results contrast with our prior finding that dishwasher is more energy intensive (per gallons). Here, the synergistic savings occur because (i) the dishwasher uses less water, and (ii) the additional energy needed to run the dishwasher

pumps, etc. is less than energy required to heat the much larger volume of water and dispense it through the faucet.

In this study, we accounted only for the energy consumed by household to use water and did not include other lighting, cooking, heating cooling, entertainment, etc. energy-uses within a house nor the energy embedded to deliver potable water or treat resulting wastewater. Moreover, we only consider major indoor water appliances. However, we expect results for outdoor water uses (landscape irrigation, car washing, etc.) will be similar to toilet results we present as outdoor water uses, also and typically, use only cold water.

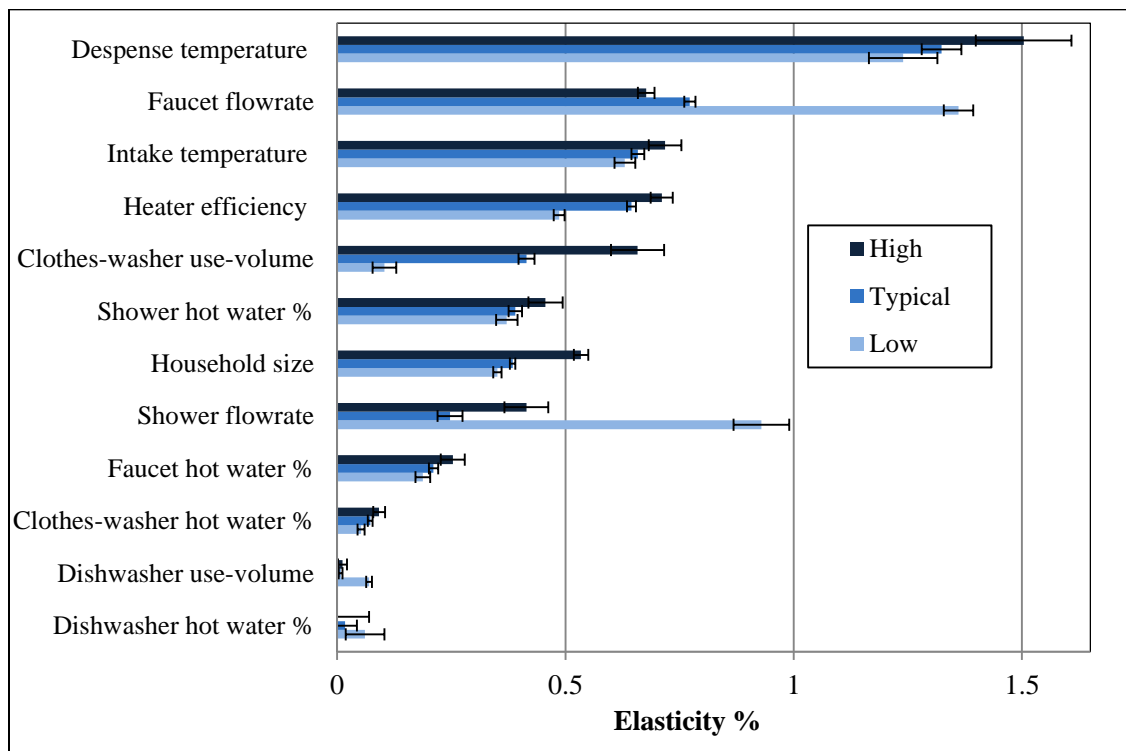


Figure 7: Relative effects of water and energy factors on household energy-use among low, typical, and high water- and energy-users (error bar represents 95% confidence interval). Models R^2 values are 0.63, 0.64, and 0.72, respectively, for high, typical, and low users.

CHAPTER 5

IMPLICATIONS FOR RESIDENTIAL WATER AND ENERGY CONSERVATION AND MANAGEMENT

Results from our analysis show that appliance technical performances (flowrate or volume per use) vary among households and across study sites. Many toilets flush at volumes higher than the Federal standards. Retrofitting standard toilets and clothes-washers to Water-Sense efficiency standards can save water and energy more than retrofitting faucets and showerheads. To conserve water, utilities should encourage customers to retrofit appliances like toilets and clothes-washers and regularly check that appliances, particularly, toilets, perform according to regulation standards.

Monte Carlo simulation results show that modeled household water-and-energy-uses are heterogenous and heavily skewed with large variations among households. We classified distinct classes of water- and energy-users and the factors affecting those classes of users: low, typical or high users. Water and energy managers should classify their customers by both their water-and-energy-uses and then target the highest users with information on potential water and energy conservation actions that can help users reduce their water-and-energy-use.

Model results also show water-energy linkages for individual appliances and that dishwashers, showers, and faucets use the most energy per gallon of water while clothes-washers and toilets use the least energy per gallon of water. Therefore, utilities should target replacing the former appliances with new appliances to save the most energy per gallon of water saved. This recommendation may be difficult to implement for dishwashers, because while installing and using a dishwasher may save water and time, it

will increase energy-use. Water and energy managers can also use water-energy linkage values to estimate the payback periods of appliance retrofits and motivate customers to install high efficient appliances. To do this, simply divide the cost of the new appliance by the money saved from reduced water-and-energy-use.

Regression results also show the relative effects of water and energy factors on household energy-use for different classes of users. These results show the water heater dispense temperature has the largest relative influence on total household energy-use followed by the faucet flowrate, water intake temperature, and heater efficiency. Other factors like clothes-washer technical performance and, shower hot water percentage have much smaller relative effects. To save the most energy, utilities should encourage customers to turn down their water heaters to 120 °F. For low water and energy users, installing efficient showerheads can also save more energy compared to other conservation actions. Retrofitting faucets that are 10% more efficient can save more energy than similar percentage change in heater efficiency. Thus, collaborative efforts in water and energy efficiency can save more water and energy than separate efforts with less cost.

Our study draws on very large, but separate water and energy data sets for this integrated analysis. Thus, we offer several recommendations to improve further water-energy data collection, modeling, and coordination. Water and energy managers and utilities should consider:

- Using manufacture's data and sale records of water appliances and fixtures to identify the market share and growth of high-efficiency appliances within their service areas.

- Collecting energy-related data on future water customer surveys like: energy source for customer's water heater, heater age and size (gallons), dispense temperature, and efficiency.
- Collecting hot water-use data for more households over longer time periods. This data collection can help identify seasonal hot water percentages used by households and better identify correlations among energy-use factors. Similarly, collecting and using summer natural gas household consumption data to help verify energy-use modeling results.
- Collecting demographic and technologic data on their customers, and then use the collected data to identify and target users of large and energy-uses. Collection could be done online as part of web-based metering and billing systems which many customers now use.
- Increasing accessibility of already collected disaggregated water-use data to the research community. Thus, utilities would benefit from detailed and reliable research results to enhance their ability to manage water and energy demands and target water and energy customers.
- Continuing to monitor water-and-energy-uses after implementing appliance retrofits to verify that appliance performance and household behaviors persist over time.

These actions can help utilities expand the data to forecast and estimate household water-and-energy-use and potential savings from conservation actions. In follow up work, we will embed the household stochastic simulation model in a city scale optimization model that includes the energy required to extract, convey, treat, and supply water to houses, and treat resulting wastewater. Such modeling will identify cost-

effective mixes of water and energy conservation actions to achieve city-wide water and energy reduction targets.

CHAPTER 6

CONCLUSIONS

We developed a method to estimate and forecast heterogeneous indoor household water and energy-uses and show linkages among the uses. The method draws on large, new, disaggregated water-and-energy-use datasets that comprise 1.4 million water-use events in 400 households across 11 U.S. cities and water heater efficiencies, cold water intake, and hot water heater dispense temperatures for 709 water heaters models in 74 U.S. cities. The method considers variations among households of demographic, behavior, and technologic water-and-energy-use factors affecting water-and-energy-uses.

We also compared variations across study cities and identified correlations among factors. We then used Monte-Carlo simulations to propagate uncertain water and energy factors to forecast heterogeneous household water and energy-uses. Finally, for the first time, we used regressions to describe and quantify the relative effects of water and energy factors on household energy-use. The approach explicitly considers household heterogeneity and improves over prior models that use deterministic, average, or homogeneous data and do not consider correlations among water-use factors.

Results show that household behaviors are similar across study sites whereas appliance technological performances differ. Distributions of household water-and-energy-uses are heavily skewed and show large variations among households. Dishwashers have the highest energy-water linkage and use more energy per gallon of water than any other appliance; clothes-washers and toilets use the least energy per gallon. However, results show that dishwasher presence in a household will lead to save more water and energy than using a faucet to wash dishes.

As a result of our water-energy findings, utilities should target households that have high water-and-energy-uses. Asking people to turn down their water heater to 120 °F would save more energy than any other action in the typical and high water- and energy-user classes. Water conservation actions, like high-efficiency faucets for users of low water-and-energy-uses can save more energy than any other energy conservation action. Utilities also should retrofit toilets, clothes-washers, faucets and showers to drive water conservation savings.

The approach helps systematically identify water and energy relationships among heterogeneous residential water-users and find characteristics of users that consume large volumes of water and energy. These steps can help utilities identify and target high-consumption users with collaborative water and energy conservation actions.

REFERENCES

- Alina, I. R., and Bryan, W. K. (2010). "Life-cycle perspective on residential water conservation strategies." *Journal of Infrastructure Systems*, 16(1), 40-49.
- American Council for an Energy-Efficient Economy, and Alliance for Water Efficiency (ACEEE and AWE). (2011). "Addressing the energy-water nexus a blueprint for action and policy agenda." Alliance for Water Efficiency, Chicago, Ill.
- AWE (2009). "Water Conservation Tracking Tool: A user guide, version1.2." Alliance for Water Efficiency, Chicago, Ill.
- Cheng, C.-L. (2002). "Study of the inter-relationship between water use and energy conservation for a building." *Energy and Buildings*, 34(3), 261-266.
- Cohen, R., Nelson, B., and Wolff, G. (2004). *Energy down the drain*, Natural Resources Defense Council & Pacific Institute, Oakland, Calif., New York, N.Y.
- Committee on Science and Technology (2009). "Energy and Water Research Integration Act: Report Together with Additional Views (to accompany H.R. 3598)"; Committee on Science and Technology, U.S. House of Representatives, U.S. Government Printing Office (GPO), Washington, D.C., December 1, 2009. <http://www.gpo.gov/fdsys/pkg/CRPT-111hrpt344/pdf/CRPT-111hrpt344.pdf>
- deMonsabert, S., and Liner, B. L. (1998). "Integrated Energy and Water Conservation Modeling." *Journal of Energy Engineering*, 124(1), 1-19.
- DeOreo, W. B. (2011). *Analysis of water-use in new single family homes*, Salt Lake City Corporation and U.S. EPA, USA, Boulder, Colo.
- DOE (2010) Department of Energy. "Residential heating products final rule analytical tools."
<http://www1.eere.energy.gov/buildings/appliance_standards/residential/heating_products_fr_spreadsheets.html> (March 2012).
- Energy Star (2012 ^a). "About ENERGY STAR."
<http://www.energystar.gov/index.cfm?c=about.ab_index> (March 2012, 2012).
- Energy Star (2012 ^b). "Clothes Washers for Consumers."
<http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=CW> (March, 2012).
- Energy Star (2012 ^c). "Dishwashers Key Product Criteria."
<http://www.energystar.gov/index.cfm?c=dishwash.pr_crit_dishwashers> (March, 2012).

- EPA (2005). "Water and energy savings from high efficiency fixtures and appliances in single family homes" US EPA-Combined Retrofit Report.
- EPA-WaterSense (2010). "Water Sense: EPA Partnership Program."
 <http://www.epa.gov/WaterSense/about_us/index.html> (June, 10, 2010).
- Hoak, D. E., Parker, D. S., and Hermelink, A. H. (2008). How energy efficient are modern dishwashers? Florida Solar Energy Center, Fla.
- Hopp, W. J., and Darby, W. P. (1980). Household water conservation: The role of indirect energy savings. *Energy*, 5(12), 1183-1192.
- Koeller, and Dietemann (2011). *National efficiency standards and specifications for residential and commercial water using fixtures and appliances. Adapted from information provided by the U.S. EPA office of water, the Alliance for Water Efficiency, and other sources*. Alliance for Water Efficiency, Chicago, Ill.
- Koomey, J. G., Dunham, C., and Lutz, J. D. (1995). "The effect of efficiency standards on water-use and water-heating energy-use in the U.S.: A detailed end-use treatment." *Energy*, 20(7), 627-635.
- Kruskal, W. H., and Wallis, W. A. (1952). "Use of ranks in one-criterion variance analysis." *Journal of the American Statistical Association*, 47(260), 583-621.
- Larson, E., Froehlich, J., Campbell, T., Haggerty, C., Atlas, L., Fogarty, J., and Patel, S. N. (2012). "Disaggregated water sensing from a single, pressure-based sensor: An extended analysis of HydroSense using staged experiments." *Pervasive and Mobile Computing*, 8(1), 82-102.
- Law, A. M., and Kelton, W. D. (1991). *Simulation modeling and analysis*, McGraw-Hill, New York, N.Y.
- Massey, F. J., Jr. (1951). "The Kolmogorov-Smirnov Test for Goodness of Fit." *Journal of the American Statistical Association*, 46(253), 68-78.
- Mayer, P. W., DeOreo, W. B., and Foundation, A. R. (1999). Residential end uses of water, AWWA Research Foundation and American Water Works Association, Denver, Colo.
- Mayer, P. W., DeOreo, W. B., Towler, E., and Lewis, D. M. (2003). "Residential indoor water conservation study: Evaluation of high efficiency indoor plumbing fixture retrofits in single-family homes in the East Bay Municipal Utility District Service Area." Aquacraft, Inc. Water Engineering and Management, Boulder, Colo.
- Ohnaka, T., Tochihara, Y., and Watanabe, Y. (1994). "The effects of variation in body temperature on the preferred water temperature and flow rate during showering." *Ergonomics*, 37(3), 541-546.

- Rosenberg, D. E. (2007). "Probabilistic estimation of water conservation effectiveness." *Journal of Water Resources Planning and Management*, 133(1), 39-49.
- Ryan, S., Long, R., Lauf, d., Ledbetter, M., and Reeves, A. (2010). "*ENERGY STAR Water Heater Market Profile*." U.S Department of Energy Silver Spring, Md.
- Steyvers, M. (2011). *Computational Statistics with Matlab (P205C), Coursebook*. Department of Cognitive Sciences University of California, Irvine.
- Suero, F. J., Mayer, P. W., and Rosenberg, D. E. (2012). "Estimating and Verifying United States Households' Potential to Conserve Water." *Journal of Water Resources Planning and Management*, 138(3), 299-306.
- Tellinghuisen, S. (2009). *Water Conservation = Energy Conservation*. Western Resource Advocates, Boulder, Colo.
- Tribus, M. (1969). *Rational descriptions, decisions, and designs*, Pergamon Press, New York, N.Y.
- U.S. Census Bureau (2010). "The U.S. Census Bureau today released the Profile of General Population and Housing Characteristics: 2010 for the United States." <<http://2010.census.gov/news/releases/operations/cb11-cn144.html>> (March, 2011).
- Vickers, A. (2001). *Handbook of Water Use and Conservation*, Waterplow Press, Amherst, Mass.
- Weihl, J. S., and Kempton, W. (1985). "Residential hot water energy analysis: Instruments and algorithms." *Energy and Buildings*, 8(3), 197-204.
- Wolff, G., Gaur, S., and Winslow, M. (2004). *User manual for the Pacific Institute Water to Air Models*, Version 1. Pacific Institute, Oakland, Calif.

APPENDIX

Table A1: Current and historic water appliance technical performances (Energy Star 2012^b; Energy Star 2012^c; Koeller and Dietemann 2011; Vickers 2001)

| Appliance | 1950-1980 | 1980-1994 | 1992-present | 2007-present | 2010-present |
|------------------------------|-----------------------------|----------------|--|-------------------|--|
| Toilet (gallon/flush) | 7.0 ^a , 5.0, 5.5 | 3.5, 4.0, 4.5 | 1.6 ^b | 1.28 ^c | |
| Showerhead (gallon/minute) | 5.0-8.0 | 2.75, 3.0, 4.0 | 2.5 ^b | 2.0 ^c | |
| Faucets (gallon/minute) | 3.0-7.0 | 3.0-2.75 | 2.2 ^b | 2.0 ^c | |
| Clothes-washer (gallon/load) | 56.0 | 51.0 | 39, 43, 27 ^d | | 14 ^h |
| Dishwasher (gallon /load) | | 14.0 | 9.5-12 ^e , 7.0-10.5 ^f , 4.5 ^g | | 4.5 ⁱ , 6.5 ⁱ , 3.5 ^j , 4.25 ^j |

^a pre 1950s; ^b EP Act 1992; ^c Water-Sense; ^d 1998-present; ^e 1990-1995; ^f 1995-present; ^g 1997-present; ^h Energy Star; ⁱ Federal standard (compact and standard models) ; ^j Energy Star (compact and standard models)

Table A2: Literature sources for water-energy parameters for major household appliances (gallon = 3.81 liter; °F -32*5/9=°C)

| End-use | Hot water percentage (%) | Water temperature (°F) | Energy factor (KWh/gallon*) | References |
|----------------|--------------------------|------------------------|-----------------------------|---|
| Shower | 57.0-73.0 (3) | 105.0-110.8 (4) | 0.097-0.140 (1) | (Cheng 2002; Cohen et al. 2004; DeOreo and Mayer ; Hopp and Darby 1980; Koomey et al. 1995; Ohnaka et al. 1994; Tellinghuisen 2009) |
| Faucet | 25.0-75.6 (5) | 80.0-105.0 (4) | -- | (Alina and Bryan 2010; Cohen et al. 2004; DeOreo and Mayer ; Hopp and Darby 1980; Mayer et al. 2003; Tellinghuisen 2009; Wolff et al. 2004) |
| Clothes-washer | 15.3-29.0 (4) | 78.0-100.0 (3) | 0.102 (1) | (AWE 2009; Cohen et al. 2004; DeOreo and Mayer ; Hopp and Darby 1980; Koomey et al. 1995; Mayer et al. 2003) |
| Dishwasher | 100.0 (3) | 139.0-140.0 (3) | -- | (AWE 2009; Hopp and Darby 1980; Mayer et al. 2003; Tellinghuisen 2009) |

Parenthesis Indicate number of studies that reported the value

* Volume of water end-use